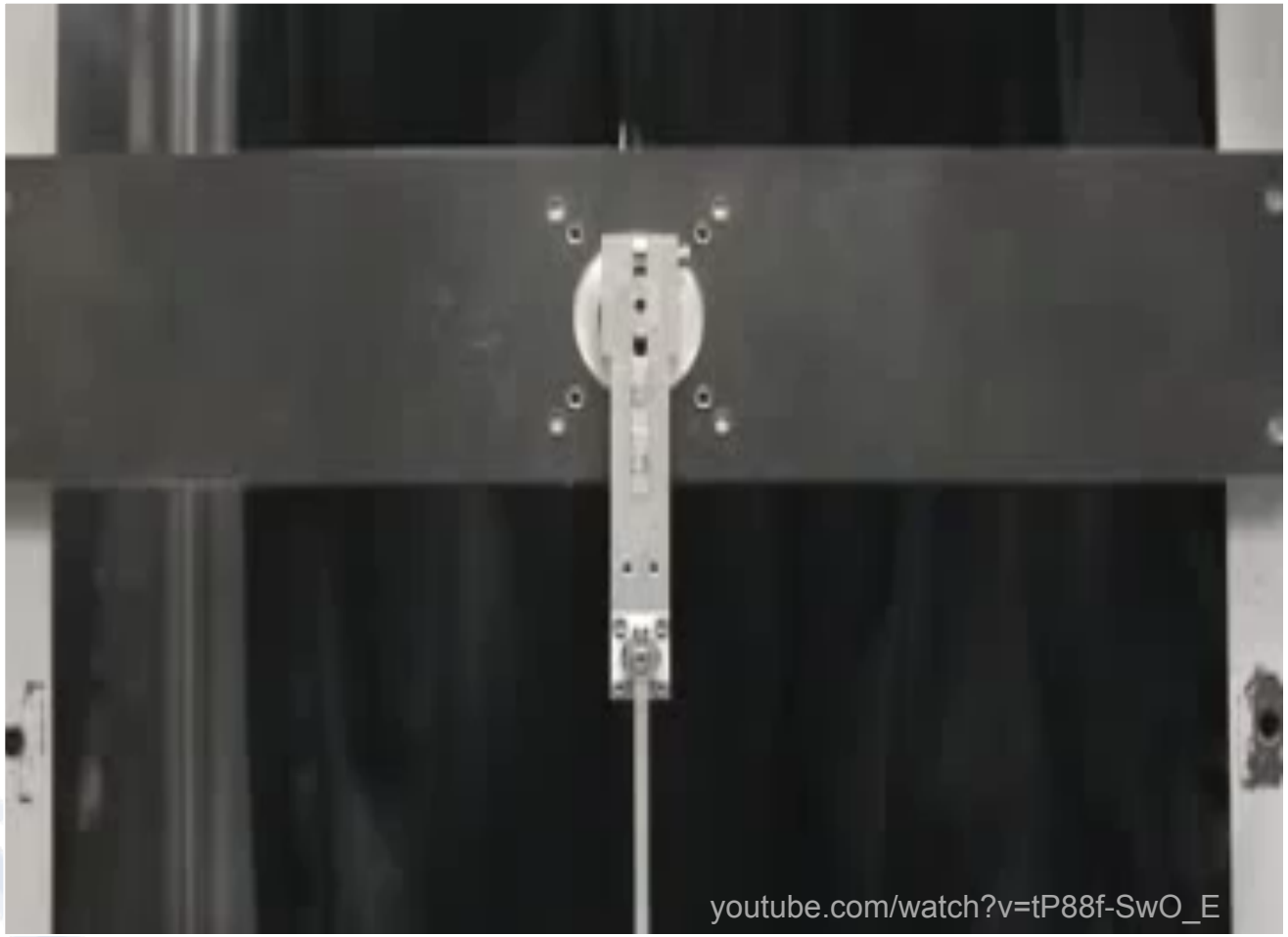
Light-induced new states of matter in solids: Prospects, concepts, and challenges

Michael A. Sentef
MPSD Theory Department

prior work at

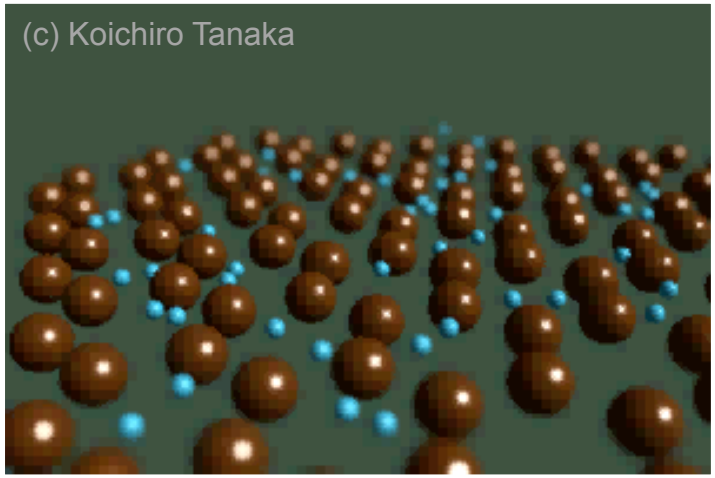
Driven is different

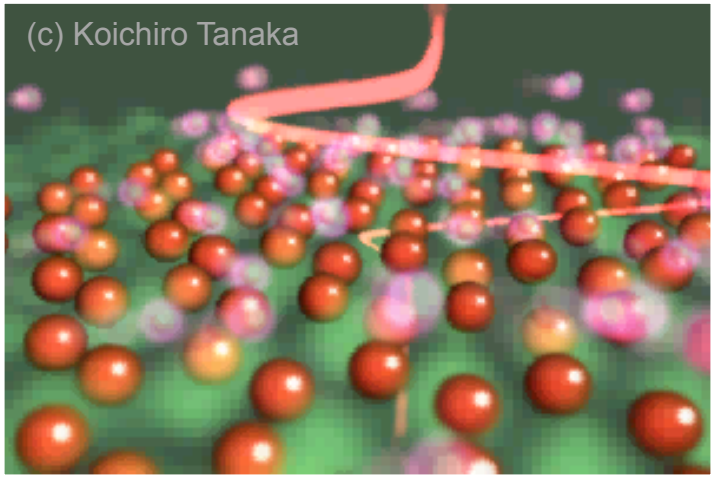
Kapitza pendulum



dynamical stabilization of a metastable state

Driven is different





H

$H(t)$

H_{eff} ?

dynamical stabilization of metastable states?
or even completely „new states“?

Outline

Prospects
Concepts
- Floquet engineering in a nutshell
- Link to time-resolved spectroscopy

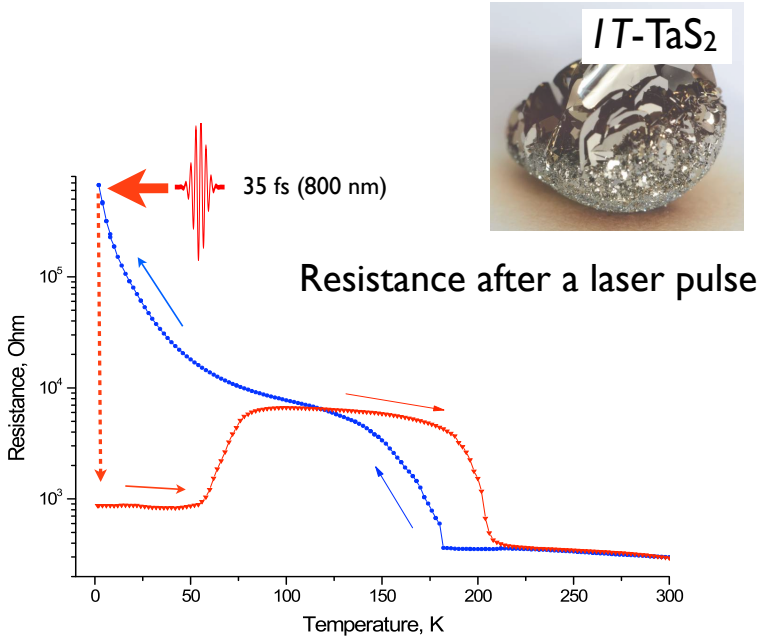
Challenges

from model concepts to ab initio simulations

- Hannes Hübener
- Umberto de Giovannini

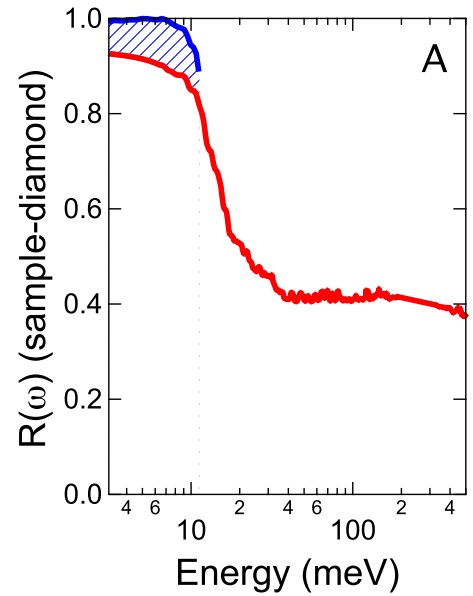
Prospects of laser control

Exposing hidden states



L Stojchevska et al. Science 2014;344:177-180

Transient new states?



Possible light-induced superconductivity in K_3C_{60} at high temperature

M. Mitrano, A. Cantaluppi, D. Nicoletti, S. Kaiser, A. Perucchi, S. Lupi, P. Di Pietro, D. Pontiroli, M. Riccò, S. R. Clark, D. Jaksch & A. Cavalleri

Affiliations | Contributions | Corresponding author

Nature **530**, 461–464 (25 February 2016) | doi:10.1038/nature16522

... and many more.

challenges. requires concepts. modeling + ab initio

Floquet engineering – buzz or useful?

Photonic Floquet topological insulators

Mikael C. Rechtsman, Julia M. Zeuner, Yonatan Plotnik, Yaakov Lumer, Daniel Podolsky, Felix Dreisow, Stefan Nolte, Mordechai Segev & Alexander Szameit

Affiliations | Contributions | Corresponding authors

Nature **496**, 196–200 (11 April 2013) | doi:10.1038/nature12066
Received 17 December 2012 | Accepted 12 March 2013 | Published online 10 April 2013

Experimental realization of the topological Haldane model with ultracold fermions

Gregor Jotzu, Michael Messer, Rémi Desbuquois, Martin Lebrat, Thomas Uehlinger, Daniel Greif & Tilman Esslinger

Affiliations | Contributions | Corresponding author

Nature **515**, 237–240 (13 November 2014) | doi:10.1038/nature13915
Received 19 June 2014 | Accepted 29 September 2014 | Published online 12 November 2014

arXiv.org > cond-mat > arXiv:1509.05763

Condensed Matter > Quantum Gases

Experimental reconstruction of the Berry curvature in a topological Bloch band

N. Fläschner, B. S. Rem, M. Tarnowski, D. Vogel, D.-S. Lühmann, K. Sengstock, C. Weitenberg

Featured in Physics | Editors' Suggestion

Floquet Engineering of Correlated Tunneling in the Bose-Hubbard Model with Ultracold Atoms

F. Meinert, M. J. Mark, K. Lauber, A. J. Daley, and H.-C. Nägerl
Phys. Rev. Lett. **116**, 205301 – Published 17 May 2016

Physics See Synopsis: No Vacancy for Tunneling

Floquet engineering in a nutshell

time periodic system

$$i\partial_t \psi = H(t)\psi \qquad H(t) = H(t+T) \qquad \Omega = 2\pi/T$$

"Floquet mapping"
= Bloch state in time

$$\Psi(t) = e^{-i\varepsilon t} \sum_m \phi^m e^{-im\Omega t}$$

Floquet Hamiltonian (static eigenvalue problem)

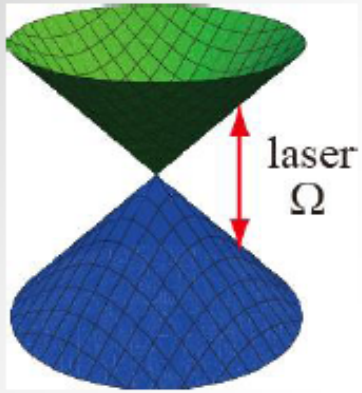
$$\sum_{m=-\infty}^{\infty} \mathcal{H}^{mn} \phi_\alpha^m = \varepsilon_\alpha \phi_\alpha^n$$

ε: Floquet quasi-energy

$$(\mathcal{H})^{mn} = \frac{1}{T}\int_0^T dt H(t) e^{i(m-n)\Omega t} + m\delta_{mn}\Omega I$$

~ absorption of m "photons"

Floquet spectrum: Dirac model + circularly polarized laser



coupling to AC field

$$\boldsymbol{k} \longrightarrow \boldsymbol{k} + \boldsymbol{A}(t)$$

$$k = k_x + ik_y$$
$$\boldsymbol{A}(t) = (F/\Omega \cos \Omega t, F/\Omega \sin \Omega t)$$
$$A = F/\Omega$$

time dependent Schrodinger equation

$$i\partial_t \psi_k = \begin{pmatrix} 0 & k + Ae^{i\Omega t} \\ \bar{k} + Ae^{-i\Omega t} & 0 \end{pmatrix} \psi_k$$

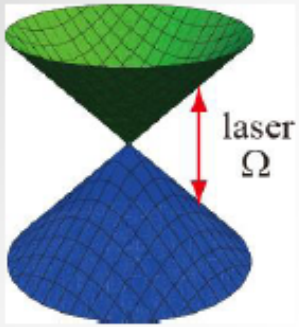
$$(\mathcal{H})^{mn} = \frac{1}{T}\int_0^T dt H(t) e^{i(m-n)\Omega t} + m\delta_{mn}\Omega I$$

$$H^{\text{Floquet}} = \begin{pmatrix} \Omega & k & 0 & A & 0 & 0 \\ \bar{k} & \Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & k & 0 & A \\ A & 0 & \bar{k} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\Omega & k \\ 0 & 0 & A & 0 & \bar{k} & -\Omega \end{pmatrix}$$

truncated at m=0,+1, -1 for display

Floquet spectrum: Dirac model + circularly polarized laser

TO, Aoki 2009



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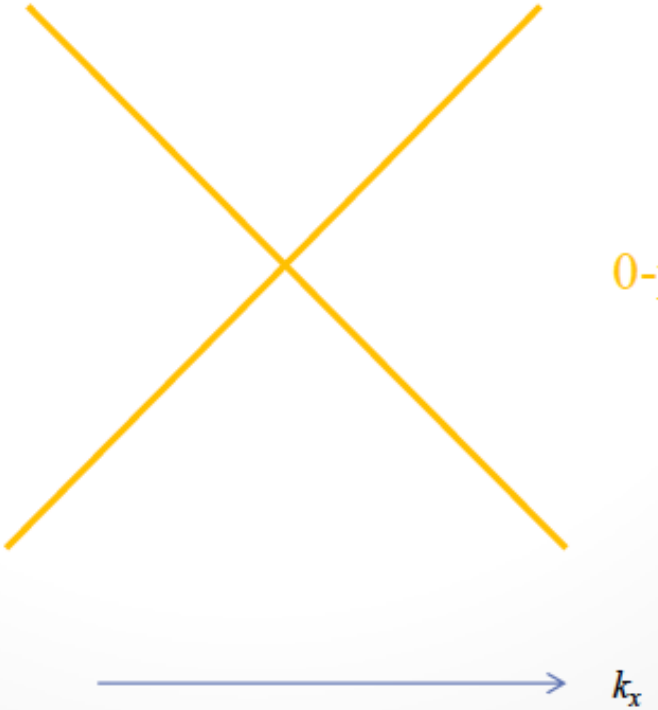
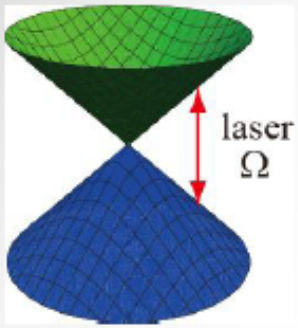
0-photon absorbed state



0-photon absorbed state

Floquet spectrum: Dirac model + circularly polarized laser

TO, Aoki 2009



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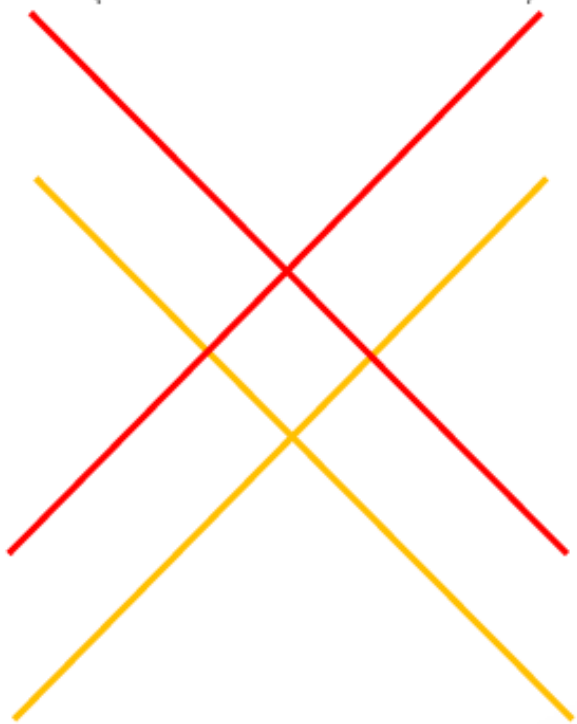
1-photon absorbed state

0-photon absorbed state



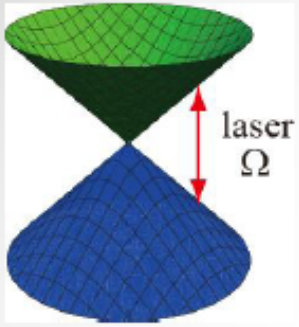
1-photon absorbed state

0-photon absorbed state

k_x

Floquet spectrum: Dirac model + circularly polarized laser

TO, Aoki 2009



$$H^{\text{Floquet}} = \begin{pmatrix} \Omega & k & 0 & A & 0 & 0 \\ \bar{k} & \Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & k & 0 & A \\ A & 0 & \bar{k} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\Omega & k \\ 0 & 0 & A & 0 & \bar{k} & -\Omega \end{pmatrix}$$

1-photon absorbed state

0-photon absorbed state

-1-photon absorbed state

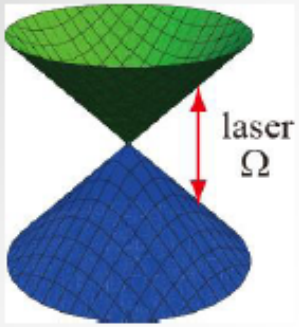
1-photon absorbed state

0-photon absorbed state

-1-photon absorbed state

Floquet spectrum: Dirac model + circularly polarized laser

TO, Aoki 2009

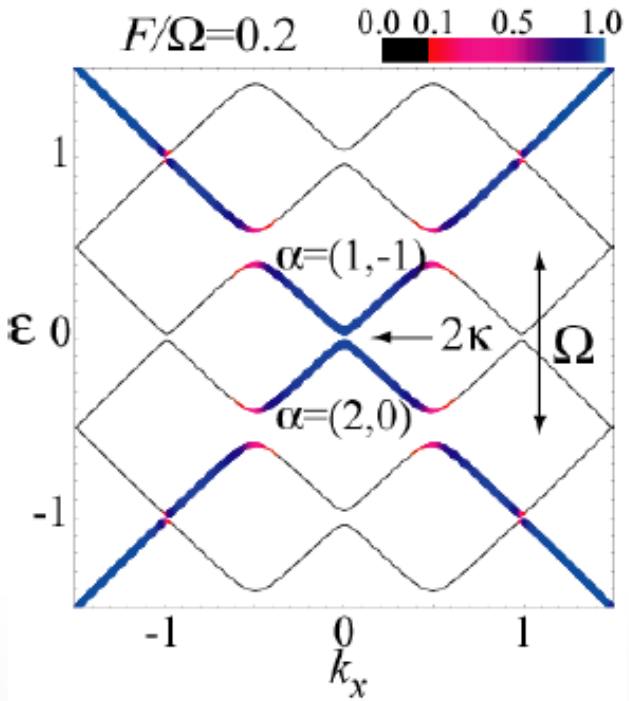


$$H^{\text{Floquet}} = \begin{pmatrix} \Omega & k & 0 & A & 0 & 0 \\ \bar{k} & \Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & k & 0 & A \\ A & 0 & \bar{k} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\Omega & k \\ 0 & 0 & A & 0 & \bar{k} & -\Omega \end{pmatrix}$$

1-photon absorbed state

0-photon absorbed state

-1-photon absorbed state



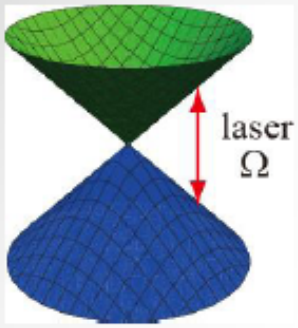
1-photon absorbed state

0-photon absorbed state

-1-photon absorbed state

Floquet spectrum: Dirac model + circularly polarized laser

TO, Aoki 2009



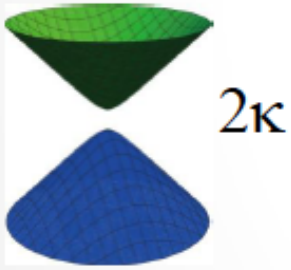
$$H^{\text{Floquet}} = \begin{pmatrix} \Omega & k & 0 & A & 0 & 0 \\ \bar{k} & \Omega & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & k & 0 & A \\ A & 0 & \bar{k} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\Omega & k \\ 0 & 0 & A & 0 & \bar{k} & -\Omega \end{pmatrix}$$

1-photon absorbed state

0-photon absorbed state

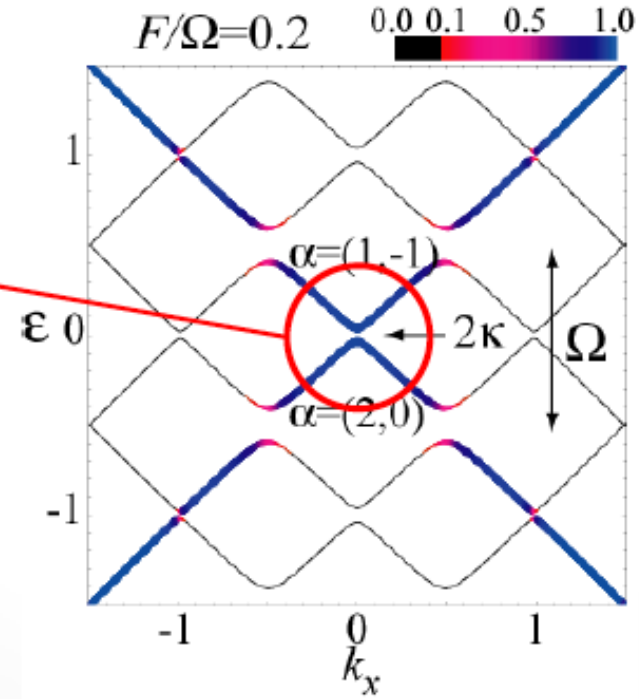
-1-photon absorbed state

near Dirac point



Dirac gap

$$\kappa = \frac{\sqrt{4A^2 + \Omega^2} - \Omega}{2} \sim A^2/\Omega$$



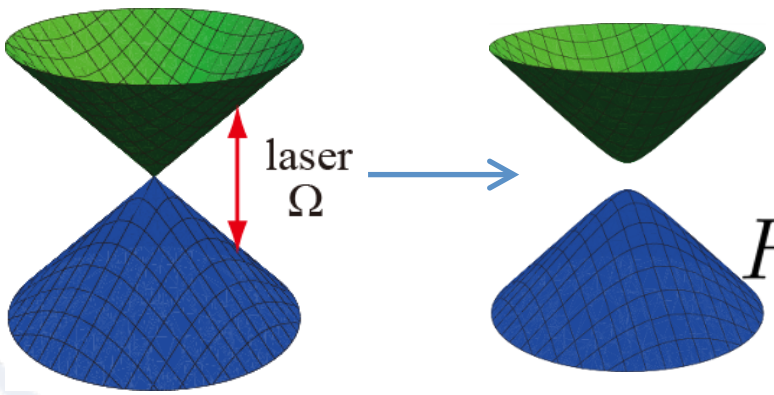
1-photon absorbed state

0-photon absorbed state

-1-photon absorbed state

Dirac fermion + circularly polarized laser

Mass term = energy gap =
synthetic field stemming from a real time-dependent field A(t)



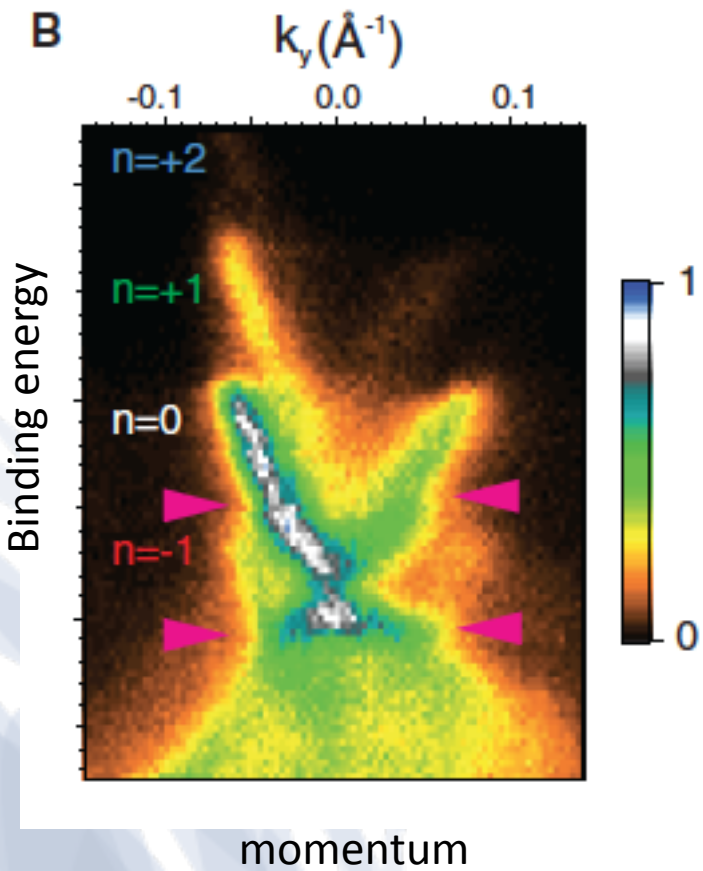
$$H_{\text{eff}} = H_0 + \frac{[\overset{\sim A\sigma_-}{H_{-1}}, \overset{\sim A\sigma_+}{H_1}]}{\Omega} + \mathcal{O}(A^4)$$

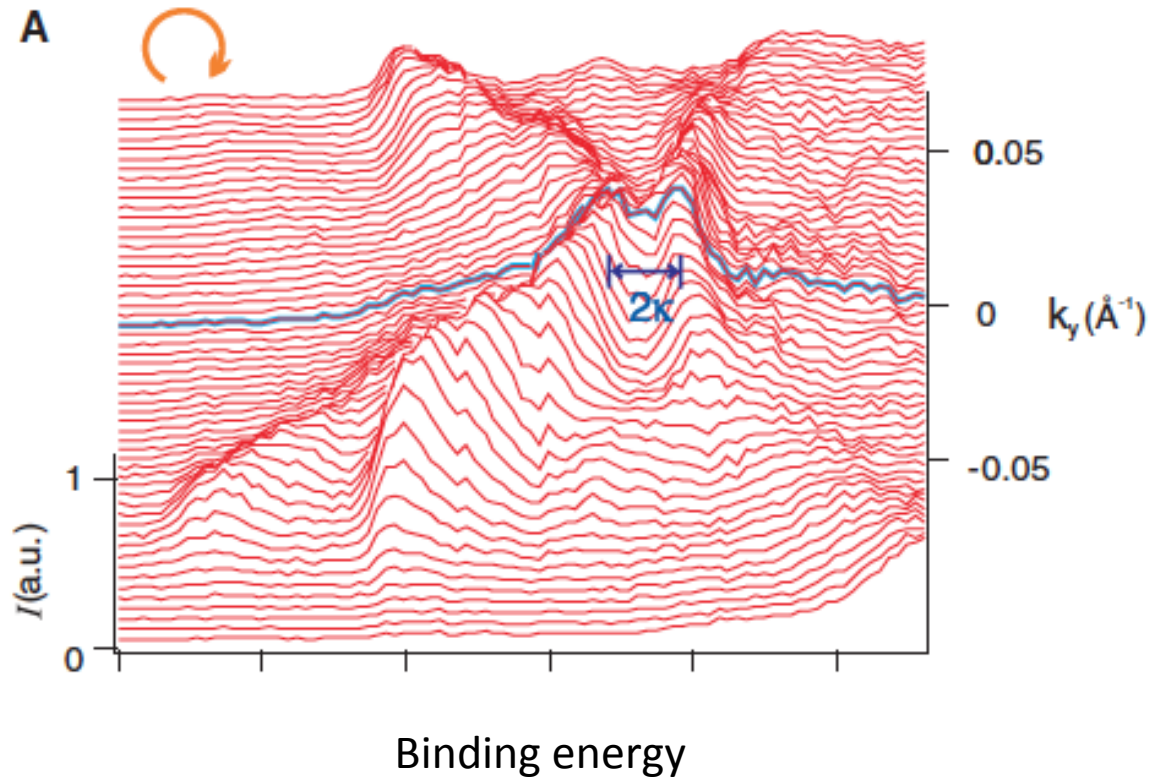
Oka and Aoki,
PRB 79, 081406 (2009)

Observation of Floquet-Bloch States on the Surface of a Topological Insulator

Y. H. Wang,* H. Steinberg, P. Jarillo-Herrero, N. Gedik†

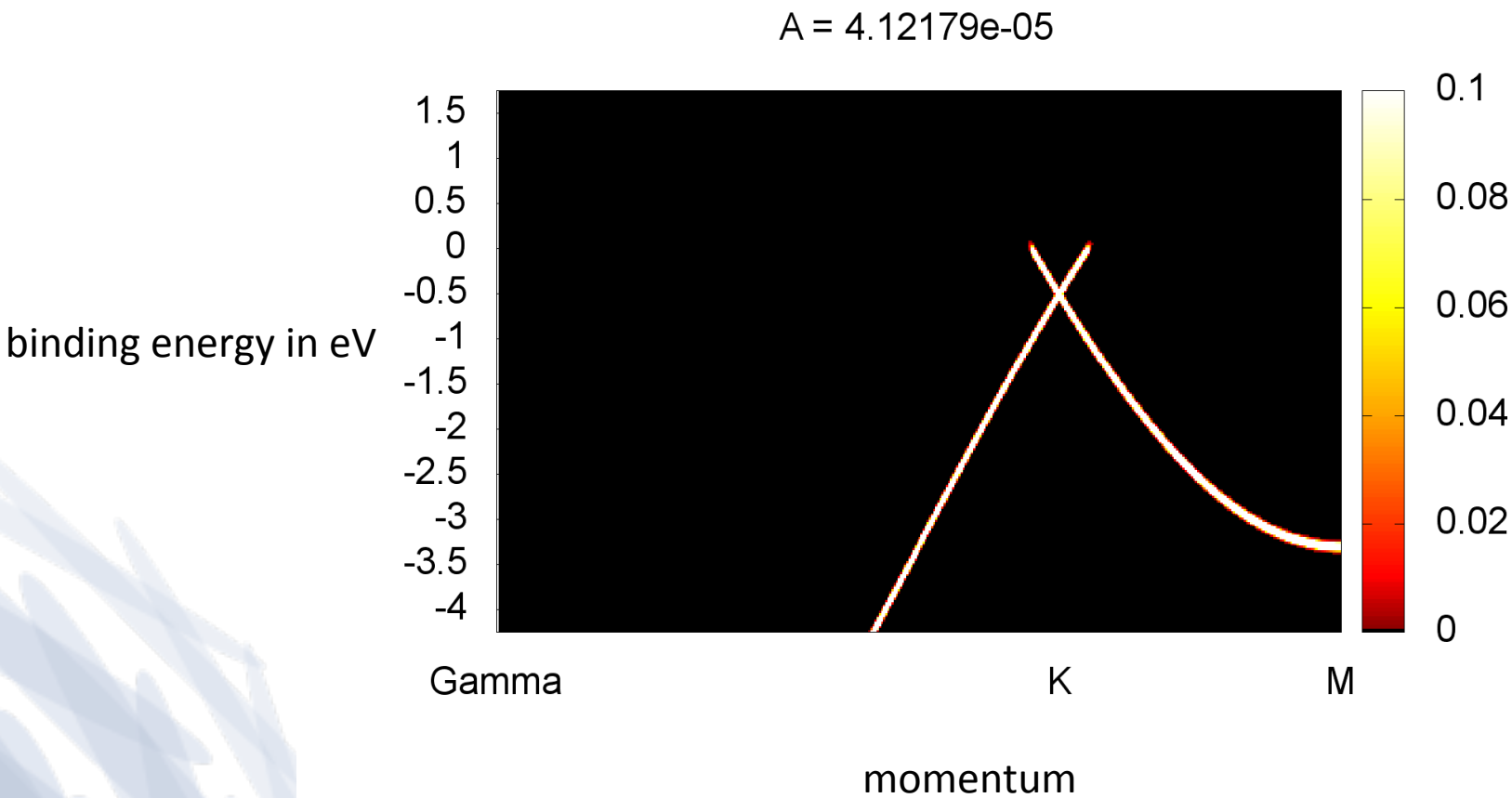
Bi_2Se_3
*Science **342**, 453 (2013)*





Floquet-Bloch states in model graphene

Time-resolved ARPES during 1.5 eV circularly polarized laser pulse



Floquet topological states in model graphene

Theory of Floquet band formation and local pseudospin textures in pump-probe photoemission of graphene

M.A. Sentef, M. Claassen, A.F. Kemper, B. Moritz, T. Oka, J.K. Freericks & T.P. Devereaux

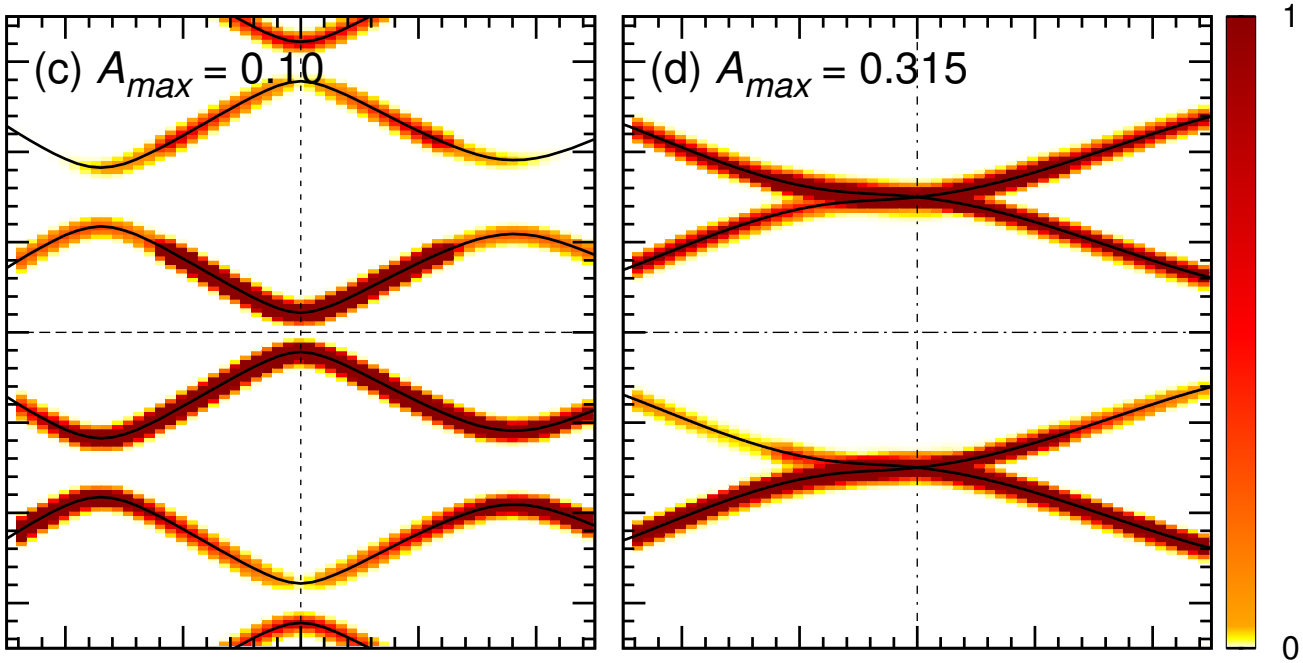
Affiliations | Contributions | Corresponding authors

Nature Communications **6**, Article number: 7047 | doi:10.1038/ncomms8047

Received 04 December 2014 | Accepted 26 March 2015 | Published 11 May 2015

Time-resolved ARPES during 1.5 eV laser pulse

binding energy

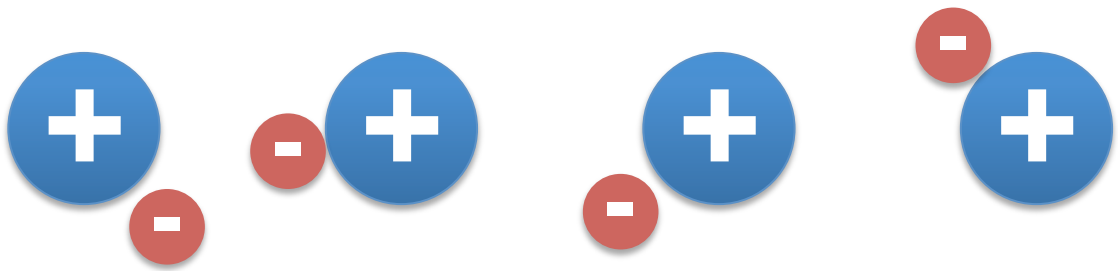


momentum

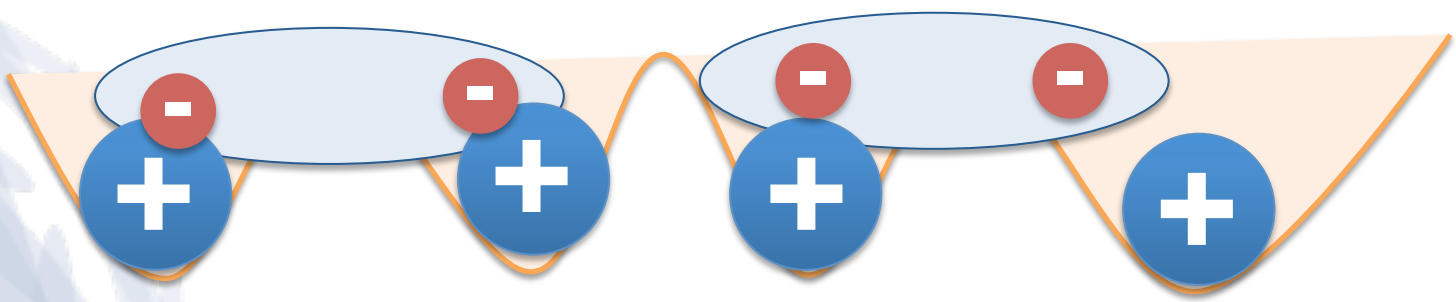
- Circularly polarized laser induces energy gap, eventually gap closing (topological transition)
- Good agreement with Floquet band structure
- should be measurable in principle (challenge to experiments ☺)

Another prospect

hypothetical high-Tc superconductor: solid hydrogen

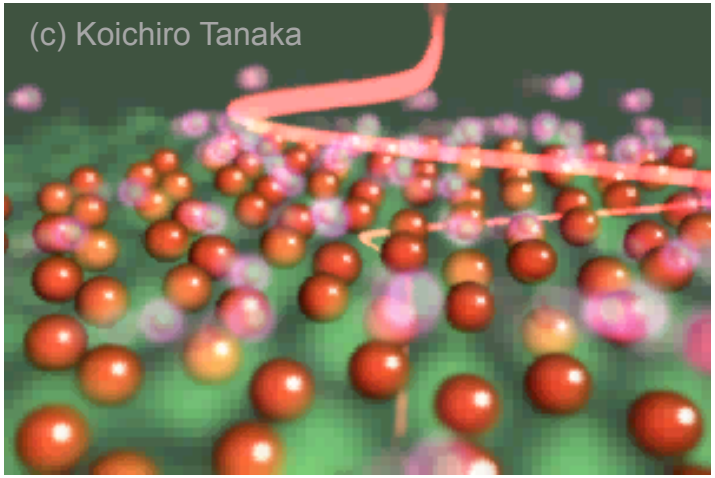


can it be engineered with a (Floquet?) laser potential? how?



Summary

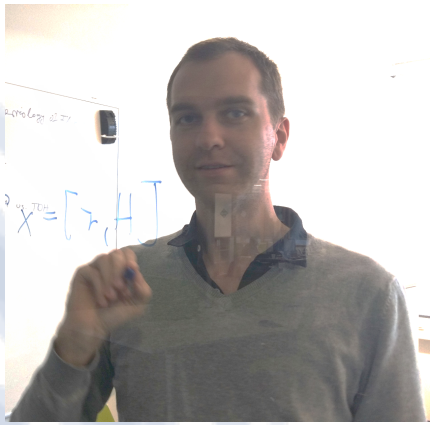
- Floquet states: engineering of fictitious gauge fields with real laser fields in solids
- laser control of topological states of matter
- examples: 2D Floquet model graphene (this talk), 3D Floquet Dirac semimetal (H. Hübener‘s talk), transition metal dichalcogenides (U. de Giovannini‘s talk)



Challenges (= ongoing and future work)

- Floquet theory provides a useful language in a specific limit (continuous driving). How far does it carry for real pump-probe experiments?
- Floquet states versus transient relaxation dynamics
- realistic laser pulses: how big are the effects?
- stabilization of light-induced states after the pulse?

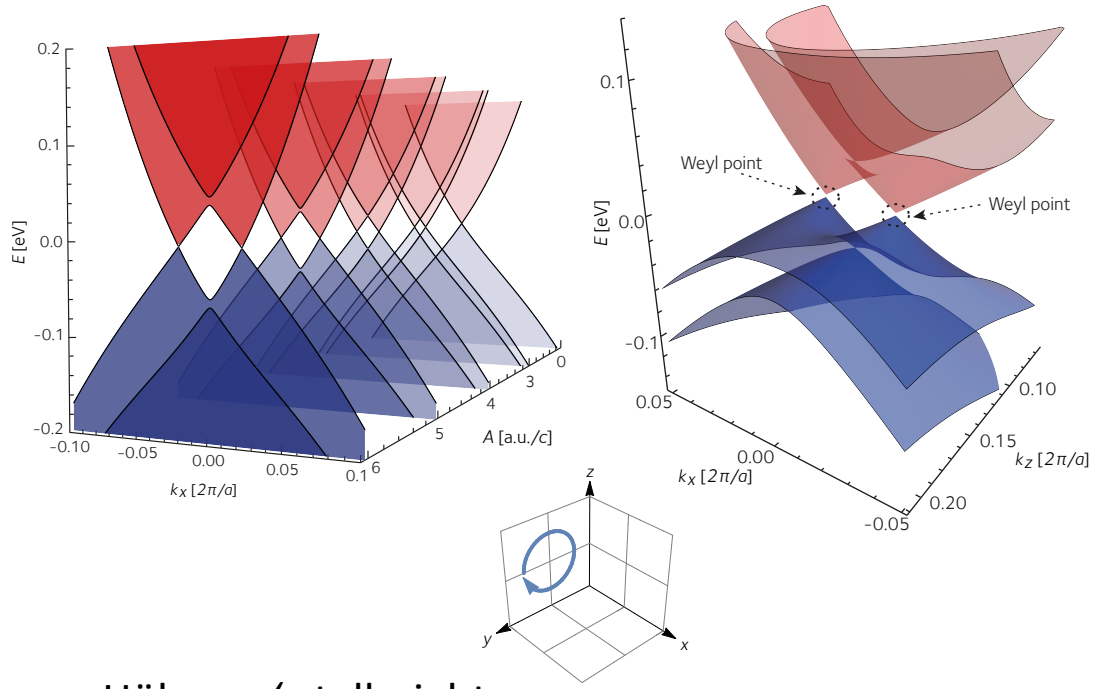
from model concepts to ab initio simulations



Hannes Hübener Umberto de Giovannini Alexander Kemper (NC State) Angel Rubio

Floquet Weyl

ab initio Floquet bandstructure: Weyl semimetal

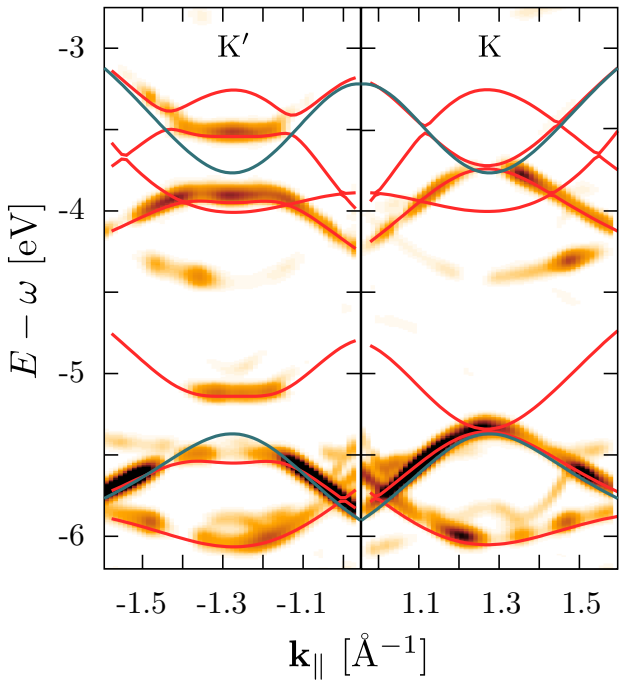


Hannes Hübener‘s talk right now

Hannes Hübener, 2nd June, Hamburg

time-resolved ARPES

- td-ARPES



Umberto de Giovannini (tomorrow)

Ads

come to Trieste

7TH INTERNATIONAL CONFERENCE

NGSCES 2016

THE NEW GENERATION IN STRONGLY CORRELATED ELECTRON SYSTEMS

ICTP TRIESTE
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We bring together a diverse group of young researchers working in the field of strongly correlated electrons to foster the exchange of ideas and stimulate new research directions. This conference focuses on state of the art and new techniques in theoretical and experimental understanding and control of strongly correlated models and materials.

FOCUS TOPICS

- Nonequilibrium quantum dynamics in correlated systems
- Strong correlations in topological insulators and spin-orbit coupled systems
- First principles correlated electronic structure: from micro to macro world
- Strongly correlated magnetism

INVITED SPEAKERS

Stephen Clark (Oxford University)
Paola di Pietro (Elettra, Trieste)
Laura Fanfarillo (CNR-IOM, Trieste)
Tom Fennell (PSI, Villingen)
John Goold (ICTP, Trieste)
Franziska Hammerath (IFW, Dresden)
Oleg Janson (TU Wien)
Mathieu Le Tacon (MPIFKF, Stuttgart)
Matteo Mitrano (University of Illinois UC)
Marco Moretti Sala (ESRF, Grenoble)
Yusuke Nomura (Ecole Polytechnique, Palaiseau)
Suchitra Sebastian (Cambridge University)
Lev Vidmar (Penn State University)
Simon Wall (ICFO, Barcelona)
Cedric Weber (King's College, London)

DATES

June 15: Abstract submission
July 1: Acceptance notification
July 15: Early bird registration
September 1: Final registration

ORGANIZERS

Daniele Fausti (Elettra, Trieste)
Adriano Amaricci (SISSA, Trieste)
Michael Sentef (MPSD, Hamburg)
Edwin Kermarrec (LPS, Orsay)

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„Theoretical simulation of pump-probe spectroscopies in solids“

starting soon

PhD and postdoc positions available!

THANK YOU!